INTRODUCTION

Henri Deslandres (1853–1948; Lequeux, 2022), defended his ‘Doctorat ès Sciences’ (1888) in the laboratory of Alfred Cornu at Ecole Polytechnique, and was hired in 1889 by Admiral Ernest Mouchez (the Director of Paris Observatory since 1878). He was in charge of organizing a spectroscopic laboratory, in the context of the development of physical astronomy initiated by Janssen (1824–1907) at Meudon (this is the physics and chemistry of celestial objects). Deslandres first built a classical spectrograph to probe the solar atmosphere\(^1\) using photographic means; he studied the line profiles of the ionized Calcium at 3934 Å wavelength (the Call K line);\(^2\) he succeeded in resolving the fine structure of the core in 1892. This was the starting point of the great adventure of spectroheliographs in France. With a classical spectrograph, monochromatic images can be delivered by an output slit located in the spectrum (selecting the light of a spectral line) when the input slit scans the solar surface. This is possible by moving the solar image onto the first slit (Janssen, 1869). The photographic spectroheliograph was invented on this basis by George Hale (1868–1938) in Kenwood, USA (1892) and by Henri Deslandres in Paris (1893), simultaneously but independently. The story is described in detail by Malherbe (2023).

Many spectroheliographs were built in the world following Hale and Deslandres techniques. For instance, a long series of continuous observations in the Call K line was collected by the spectroheliographs at Kodaikanal in India, Mount Wilson in the USA, Mitaka in Japan, Sacramento Peak in the USA, Coimbra in Portugal, Meudon in France and Arcetri in Italy. They produced extended archives, some of them covering up to 10 eleven-years solar cycles, which have proved very useful when investigating long-term solar activity and rare events (such as energetic flares, huge sunspot groups or giant filaments).\(^3\) The Call K3 and H\(\alpha\) central intensities are very convenient for imaging spectroscopy of the chromosphere (filaments, prominences, magnetized bright plages, in the altitude range 1500–2000 km); the wings of the Call K line (K1v) formed in the lower range (200–500 km) are good tracers of sunspots and faculae.\(^4\) The Call K line is mainly sensitive to temperature fluctuations, while H\(\alpha\) is more sensitive to density. In parallel, between 1919 and 1939, ‘section’ spectroheliograms of Call K were systematically obtained at Meudon. In that case, instead of moving continuously, the entrance slit of the spectrograph scanned the Sun in steps of 20–25°, forming on the photographic plate full spectra of cross sections of the Sun. The spectral width was about 2 Å, allowing the evaluation of the Doppler shifts\(^5\) of the Call K3 component (the line core). Such observations were unique, but the derivation of radial velocities was, of course, a purely manual and long task. For that reason, this program was abandoned in 1939 at the start of WWII, and was never restarted later. However, the 2017 version of the Meudon
spectroheliograph (Malherbe et al., 2023), with a fast sCMOS numerical detector, registers the full line profiles and provides now 3D FITS data-cubes (x, y, λ), in the astronomical standard format, which are available on-line and allow Doppler shift determinations and more parameters using line inversion techniques.

This paper reviews briefly fifty years of monochromatic observations carried out at Meudon Observatory, during the first half of the twentieth century, under the auspices of Lucien d’Azambuja (1884–1970, Figure 1), who retired in 1954. Section 2 describes systematic observations started in 1908. Section 3 relates the studies performed by Lucien and Marguerite d’Azambuja (born Roumens, 1898–1985, Figure 1), forming together the famous team of filament and prominence explorers, until 1959. Section 4 summarizes special observations of various spectral lines, made before 1930 for L. d’Azambuja’s thesis with the 7-metre spectroheliograph, which demonstrated that the initial choice of CaII K and Hα was the best for imaging spectroscopy of the chromosphere. Section 5 presents rare events of solar activity observed with the more classical 3-metre spectroheliographs and Section 6 summarizes the international role of the d’Azambujas.

2 SYSTEMATIC OBSERVATIONS AT MEUDON

Systematic observations started in 1908 for CaII K and 1909 for Hα with the new spectroheliographs installed in Meudon by Deslandres and d’Azambuja (Deslandres, 1910; d’Azambuja, 1920a; 1920b; 1930) as shown by Figures 2, 3, 4. Details of the optical setup were summarized by Lequeux (2022) and Malherbe (2023). A spectrohelioscope (Figure 5) working in Hα came in the fifties for visual inspection of solar activity. It was a removable device composed of a rotating prism in front of the entrance slit (to scan the Sun) and a second one at the output slit selecting the Hα line in the spectrum; the high-speed rotation of both prisms gave an observer the impression of seeing a monochromatic image at the eyepiece, because of retinal persistence.

Figure 1: Marguerite and Lucien D’Azambuja, November 1939, the day of P. Phu’s PhD. Key. Astronomers: 1 = M. d’Azambuja (42 years old); 2 = L. d’Azambuja (55 years old); 3 = B. Lyot; 4 = R. Servajean. Visiting astronomer: 5 = P. Phu. Others: 6 = Mrs Lyot; 7 = Mrs Servajean (courtesy: Paris Observatory).
Figure 2: The two-mirror coelostat with Lucien d’Azambuja in 1921 (courtesy: Gallica/BNF, Meurisse agency).

Figure 3: The spectroheliograh with Lucien d’Azambuja in 1921 (courtesy: Gallica/BNF, Meurisse agency).
Figure 4: The spectroheliographs designed by Deslandres and d’Azambuja in 1908. The entrance objective ($f = 4.0$ m, $a$) delivers a 37.2 mm image and scans the Sun with the carrier ($C$), velocity transformer ($T$), motor ($M$). The spectrograph slit ($b$), the collimator ($f = 1.3$ m, $c$) are common to all configurations. Top: spectroheliographs for systematic observations in CaII K (three prisms $g$, left panel) and Hα (grating $d$, right panel). Both use a 3 m focal length chamber with an output slit in the spectrum ($i$, $f$). The photographic glass plate holders are motorized and move 2.31 times faster (the optical magnification) than the imaging objective. The diameter of the Sun is 86 mm on plates. Bottom: the high dispersion spectroheliograph for research. It uses either the grating ($d$) or prisms ($g$). $h$ is a flat mirror. $l$ is a 7 m concave chamber that forms a spectrum in ($m$). The diameter of the Sun is there 205 mm. After this comes an afocal reducer composed of a second 7-m concave mirror ($n$) and lenses ($p$, $q$, $r$) providing various magnifications on the photographic plate and output slit ($s$). There is a prism ($o$, 30°) to reject parasitic light or unwanted orders.

Figure 5: The visual spectrohelioscope in the fifties with L. d’Azambuja in the insert (courtesy: Paris Observatory).
Systematic observations were performed with two 3-metre spectroheliographs (Figures 3, 4 and movie 1): spectrograph n°I for CaII K using 3 prisms of 60° at minimum deviation, providing a spectral resolution of 0.15 Å, and spectrograph n°II for Hα using a Rowland plane grating, 568 grooves/mm, providing in the first order a spectral resolution of about 0.40 Å. The focal length of the scanning objective was 4.0 m, and the magnification of the spectrographs was 2.31 (3.0 m chamber, 1.30 m collimator), so that the size of the Sun on the photographic glass plates was 86 mm. The width of the entrance slit was 0.03–0.04 mm (1.5′–2′) well adapted to the usual seeing of 2″ in Meudon; while the second slit in the spectrum was 0.075 mm wide.

From 1908 to WWI (1914), observations consisted of daily spectroheliograms in CaII K3 (line centre, chromosphere), CaII K1v (violet line wing, photosphere) and Hα centre (chromosphere). Formation heights of K3, K1 and Hα lines are reported in Figure 6. Observations were totally interrupted during WWI. Figure 7 shows typical observations performed daily from 1919 to 1939 until the start of WWII. During this period, CaII K3, CaII K1v and Hα were continued, and a ‘section’ spectroheliogram (Figure 8) with an enlarged slit in the spectrum (1 mm = 2 Å) was added for Doppler shift measurements of the CaII K line; for that purpose, full spectra of 86 cross sections of the solar surface were recorded by spatial steps of about 1 mm = 22″. Contrarily to WWI, observations were not stopped by WWII, but the lack of manpower was an important constraint, so that ‘section’ spectroheliograms were abandoned, and never restarted after WWII. Typical systematic observations made after WWII by the d’Azambujas (Figure 9) are shown in Figure 10; they still include the initial choice of 1909 (CaII K3, K1v and Hα), plus a long exposure CaII K3 for limb features and prominences, with a disk attenuator (because prominences are 5–10 times fainter than the disk).
All data since 1908 are freely available online at https://bass2000.obspm.fr, in 12 bits FITS and 8 bits JPEG format, for images after 1980, and in JPEG only for older spectroheliograms (250 dpi scans of glass and film plates). A new scan at 600 dpi/16 bits is in progress and should be completed in 2025. The collection is one of the longest world-wide, with more than 100000 images along 10 solar cycles.

The spectroheliograph dedicated to daily observations was revisited in the eighties. The prisms (for Call K) and plane grating at order 1
Figure 9: Astronomers working at Meudon Observatory in 1950. Key: 1 = M. d’Azambuja; 2 = L. d’Azambuja; 3 = H. Grenat; 4 = A. Dollfus; 5 = F. Baldet; 6 = R. Herman (courtesy: Paris Observatory).

(for Hα) were replaced by a unique 300 grooves/mm grating (blaze angle of 17° 27') providing alternatively Hα at order 3 and Call K at order 5, without any rotation, so that the same 3-metre chamber was used for both lines. The order 4 was convenient for Hβ but the lenses were achromatized only for orders 3 (red) and 5 (violet). Interference orders were selected by coloured filters. Glass plates were abandoned and systematic observations were produced in this new configuration with 13 x 18 cm² film plates until year 2000. Almost real time digitization of films started in 1995 with a 12 bits scanner and images were archived by the BASS2000 data base when it was commissioned in 1996.

The second slit in the spectrum was removed in 2001 when film plates were replaced by a back illuminated CCD camera (1340 x 100 format) from Princeton Instruments (14 bits dynamic range, 20 µm pixels), reducing the chamber focal length from 3.0 m to 0.9 m. Finally, full line profiles are recorded (movie 2 for x-direction surface scans and wavelength exploration of final Call K and Hα data-cubes). The spectral sampling of Call H and K is 0.093 Å (order 5), while the one of Hα is 0.155 Å (order 3). The spectral domain of usual observations is 9 Å and 6 Å, respectively for Call H, K, and Hα. The spatial sampling is about 1.1", which is quite convenient for the standard Meudon seeing of 2". The width of the entrance slit of the spectrograph never changed (0.03 mm) and corresponds to 1.55" on the solar surface.

3 MR AND MRS D’AZAMBUJA, THE FAMOUS PROMINENCE EXPLORERS

Lucien d’Azambuja was hired in 1899 by Deslandres when he was only 15 years old (Martres, 1998; Rösch, 1970). He completed in parallel his studies in mathematics and physics at Paris University (la Sorbonne). Marguerite Roumens arrived at Meudon in 1925 and participated in d’Azambuja’s spectral line observing program (Section 4) with the 7-metre spectroheliograph; the original results were reported in his thesis (d’Azambuja, 1930). They got married and began a monumental joint research project on solar filaments (d’Azambuja and d’Azambuja, 1948). This memoir is considered as a ‘bible’ among Meudon solar astronomers.
Figure 10: Typical spectroheliograms after WW2 (example of 28 October 2003, the day of a massive X-class flare). Hα for the chromosphere (filaments, plages); CaII K1v for the photosphere (sunspots, faculae); CaII K3 for the chromosphere (filaments, bright plages); CaII K3 long exposure time for prominences and limb with a neutral density attenuator ND1 (10% transmission) superimposed on the solar disk (courtesy: Paris Observatory).

It contains an extensive study of the morphology, evolution and stability of solar filaments and prominences (Figure 11), and their relationships with their neighbourhood (active regions). It is a fundamental work at the base of modern solar physics. When L. d’Azambuja retired in 1954, his wife became responsible for the observations; she retired in 1959 and the d’Azambujas both left Meudon at this date, after 60 years of astronomy for Mr d’Azambuja (Malherbe, 2023)! This was an incredible career, which would be impossible to reproduce today.

This huge study of 387 filaments showed that they are thin (5000 km typical), long (10⁵ km to 10⁶ km), high (up to 50000 km) and cold (8000 K) hydrogen structures suspended in the hot corona (10⁶ K), above the chromosphere. Filaments look like vertical curtains anchored in the photosphere by legs on both sides. They exhibit extremely variable aspects due to perspective effects during the solar rotation (Figure 12 and Figure 13). When seen at the limb, filaments are bright and called prominences and they emit light in Hα or Call K. But when seen on the solar disk, filaments absorb the photospheric light in the same lines and appear dark.

**Figure 14** shows a typical example of filament evolution during a few days. D’Azambuja and d’Azambuja (1948) found that quiescent fil-
amments (far from active regions) evolve slowly and can last during several rotations (the duration of the synodic or Carrington rotation is 27.27 days, it corresponds to the rotation of zones at ±26° latitude, seen from the Earth). Their shape and length vary continuously, filaments can split into several parts, which can also reconnect. Varying perspective effects play a major role during the solar rotation. The authors found a systematic inclination (8°) of the filament blade towards the western direction. The orientation of equatorial filaments is
**Figure 13:** Various aspects of solar filaments during the rotation. Emitting light at the limb (bright prominences), or absorbing light on the disk (dark filaments) (after d’Azambuja and d’Azambuja, 1948).

**Figure 14:** Evolution of filaments and their anchoring into the photosphere (after d’Azambuja and d’Azambuja, 1948).
not far from the meridians (Figure 14), while polar ones, which appear at the beginning of a new cycle, are close to the parallels (Figure 15). The differential rotation (faster at low latitudes) affects the direction of long filaments and elongates them. We know today that filaments are dense (density of $10^{17} \text{ m}^{-3}$) and cold structures (8000 K) supported in the tenuous ($10^{15} \text{ m}^{-3}$) and hot corona (10$^6$ K) by weak magnetic fields (0.002 T) overlying the boundary between regions of opposite polarities. At the beginning of a new cycle, polar filaments delinate the frontier between the new emerging magnetic field at lower latitudes and the old polar one which reverses at the next solar maximum. The authors emphasized the importance of royal zones (the regions where sunspots form), both for the birth of active regions and filaments; they discovered that filaments migrate towards the poles, indicating the existence of a meridional circulation, which was confirmed later by helioseismology (the MDI instrument onboard SOHO/ESA/NASA).

The rotation of filaments was found similar to that of active regions and sunspots, except at high latitudes where measurements revealed a slower rotation. Among the 387 studied filaments, 141 were associated with active regions (plage filaments), while 246 were not (quiescent ones). These quiescent filaments need (in average) three rotations to develop, and start to fragment during the fourth passage across the disk. They can last up to six rotations (even twenty rotations for very quiet polar prominences) and their length increases with their lifetime. Some filaments were observed to split or merge together. They may become unstable. During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

4 SPECIAL SPECTROHELIOGRAMS AND UNUSUAL SPECTRAL LINES

During his thesis work, which he defended in 1930, Lucien d'Azambuja explored many spectral lines with the large 7-metre spectroheliograph for research, providing a much higher dispersion than the 3-metre spectroheliographs used for systematic observations (Figure 16). High dispersion is required to study thin photospheric lines such as MgI 3838 Å, SrII 4078 Å, FeI 4120 Å, CaII 8542 Å, FeI 4384 Å, MgI 5184 Å, Hα 6562 Å, NaI 5890 Å, as well as chromospheric infrared lines of CaII 8498 Å, Hα 6562 Å, FeI 4384 Å, while 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During his thesis work, which he defended in 1930, Lucien d'Azambuja explored many spectral lines with the large 7-metre spectroheliograph for research, providing a much higher dispersion than the 3-metre spectroheliographs used for systematic observations (Figure 16). High dispersion is required to study thin photospheric lines such as MgI 3838 Å, SrII 4078 Å, FeI 4120 Å, CaII 8542 Å, FeI 4384 Å, MgI 5184 Å, Hα 6562 Å, NaI 5890 Å, as well as chromospheric infrared lines of CaII 8498 Å, Hα 6562 Å, FeI 4384 Å, while 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).

During a full solar cycle (11 years), D'Azambuja and d'Azambuja (1948) counted that 206 objects partly disappeared (this was called the 'Disparition Brusque' phenomenon, or DB); while in 137 cases, the DB was only temporary. Most perturbations occurred among equatorial filaments close to active regions. We know today that the DB events can be either thermal (heating of material which vanishes in Hα) or dynamic (magnetic instability affecting the filament support, sometimes associated to flares or coronal mass ejections).
Figure 16: Dispersion of the various spectroheliographs. The 3-metre spectrographs n°I (P for prisms) and n°II (R for grating) were used only for systematic observations, respectively for CaII K and Hα lines. The multi-purpose 3-metre spectrograph n°III and the high dispersion 7-metre instrument n°IV (each with either 3 prisms, P, or plane grating, R) were used only for research work (after d’Azambuja, 1930).

Figure 17: Top: spectral lines of CaII K and Hα above a bright plage and at the limb. Bottom: CaII K and Hα in the quiet Sun observed by spatial steps of 30” (cross sections of bandwidth 3 Å). Wavelength in abscissa (after d’Azambuja, 1930).
bright Call K2v and K2r peaks (± 0.2 Å apart from the dark K3 core) are well resolved. The chromosphere appears clearly at the limb in both lines above the photosphere (which is visible in the line wings and in the continuum).

Figure 18 displays three images, respectively in the centre of Hα line and in the blue wing. Filaments are still visible at −0.25 Å, but vanish at −0.50 Å (near the inflexion points of the line profile) and the photosphere (below the chromosphere) begins to appear at −0.50 Å, except in the case of Doppler shifts (0.5 Å = 25 km/s). Such observations are interesting because they were never done daily, contrarily to the Hα centre.

Figure 19 displays three images, respectively in the centre of Call K line (K3) and in the blue wing. Filaments and bright plages are perfectly visible in K3, but this is not the case of sunspots. Filaments are barely observable at −0.25 Å (K2v) and sunspots begin to appear. But filaments completely vanish at −1.27 Å (K1v) while the photosphere, below the chromosphere, becomes clearly visible, with sunspots and bright faculae (which are located just below the chromospheric plages). Observations of K2v are particularly rare in the collection, contrarily to K3 and K1v.

Figure 20 shows an exceptional observation of the Balmer series, Hα, Hβ, Hγ, Hδ, and Hε. The contrast of filaments and plages (chromosphere) vanishes with decreasing wavelength, because lines form deeper. Conversely, sunspots appear progressively along the series, which reveals that Hα is the best choice for chromospheric structures, while Hδ or Hε are not better than Call K1v for sunspots and faculae (however Hε is contaminated by the red wing H1r of the Call H line). This observational series is the only one of the collection. Figure 21 focuses on the central part of the solar disk with active regions and filaments.

Helium lines where also tested by d’Azambuja. Figure 22 shows an exceptional observation in Hel D3 5876 Å of an active region producing the huge flare of 26 July 1946, while Figure 23 shows the first world-wide observation done in the infrared Hel 10830 Å line with a
bandpass of 0.5 Å. These observations are absolutely unique in the collection (d’Azambuja, 1938). Several decades later, Kitt Peak National Observatory started systematic observations in this infrared line of helium.

Figure 20: The Balmer series Hα, Hβ, Hγ, Hδ and Hε of hydrogen on 14 August 1947, and the CaII K3 spectroheliogram for comparison. Hα is chromospheric, but Hδ and Hε are rather photospheric (courtesy: Paris Observatory).

Figure 21: The Balmer series Hα, Hβ, Hδ and Hε on 14 August 1947 (detail of Figure 20). The contrast of filaments and plages is best in Hα and decreases drastically along the series (after d’Azambuja and d’Azambuja, 1948).
Infrared lines of CaII were studied by d’Azambuja in his thesis work. Figure 24 shows images in CaII 8498 Å and 8542 Å, on 4 September 1928, in comparison with the usual CaII K3 3934 Å. These observations are extremely rare in the collection and showed that chromospheric structures are better seen with CaII K3 (Figure 25). Several decades later, Kitt...
Peak National Observatory started systematic observations in CaII 8542 Å in order to measure chromospheric magnetic fields (which is much more difficult with CaII K).

Figure 25 shows also a detail of Figure 23, for comparison of HeI 10830 Å and Call K. While filaments appear dark in both lines, this is not the case of plages, which are bright in Call K but dark in Hel 10830 Å.

The Cal 4227 Å line was studied by d’Azambuja during the course of his thesis. Figure 26 shows images in the line core and wing, in comparison with the usual Call K1v for the photosphere. Figure 27 shows spectroheliograms in FeI 4046 Å, FeI 4202 Å, SrII 4078 Å lines. Many more photospheric lines (the list of Figure 27 indicating also the selected bandwidth in Å) were observed at high spectral resolution and a facular visibility index (0-5) was established. It clearly demonstrated that these investigated lines provided spectroheliograms...
Figure 26: Spectroheliograms on 17 May 1927 of the CaII 4227 Å line, compared to CaII K line for the photosphere (at right, for reference, the chromospheric Hα line) (after d’Azambuja, 1930).

Figure 27: Spectroheliograms in various photospheric lines, compared to CaII K line. The table lists the studied lines with their respective bandpass (in Å). The index is a measure (0 to 5) of the visibility of bright plages (after d’Azambuja, 1930).
RARE SOLAR ACTIVITY EVENTS OBSERVED WITH THE SPECTROHELIOGRAphs

5 RARE SOLAR ACTIVITY EVENTS OBSERVED WITH THE SPECTROHELIOGRAphs

The centennial Meudon collection of CaII K\textsubscript{1v} spectroheliograms contains plenty of information about the area covered by sunspots. In particular, the April 1947 sunspot group (Figure 28, centre) is probably the largest ever seen (6.1% of the solar disk), followed by other groups of the same solar cycle (number 18), among them the February 1946, May 1951, July 1946 (Figure 28) and March 1947 groups (respectively 5.2%, 4.9%, 4.7% and 4.6% of the disk). These observations illustrate the interest for long term observations spanning more than 10 solar cycles, because exceptional area sunspots provide an upper limit for magnetic energy that can be released in solar flares. Please refer to Malherbe (2023) for more details on such events.

Extremely long filaments, such as those in Figure 29 and Figure 30, delineate giant magnetic cells on the Sun. Indeed, filaments are located above the inversion line of photospheric magnetic fields; large filaments can be considered as tracers of large magnetic zones. Filaments of more than one solar radius length are not frequent and can last more than 6 rotations (Figure 30). Here again, long term collections of observations, are essential to catch rare phenomena which contribute to a better understanding of solar physics.

Fast solar activity events, such as flares, ‘Disparitions Brusques’ of filaments, prominence eruptions and mass ejections are difficult to observe with a spectroheliograph, because...
of the moderate temporal resolution. For that reason, Hα filters were used after 1950. At Meudon, high cadence observations (1 minute) of dynamic events started in 1954 with Lyot filters, in particular in the frame of the International Geophysical Year (1957). However, until this date, spectroheliographs were the only available instruments to study fast evolving phenomena, and a few exceptional active phenomena were recorded with a maximum of twelve spectroheliograms for an event lasting a few hours. It was indeed a complicated task at the epoch of glass photographic plates. The prominence eruption of 18 June 1925 (Figure 31 and Figure 32) is one of the best events available in the collection. A ‘section’ spectroheliogram (Figure 32) was even produced to estimate the radial velocities (i.e. the velocity component orthogonal to the sky plane). Of course, prominence eruptions are today commonly observed in HeII 304 Å (the Lyα line of HeII at 80000 K) with the AIA telescope onboard.
Figure 31: Instability of a solar prominence at the limb observed in CaII K on 18 June 1925 (08:46 to 11:23 UT) with Meudon spectroheliograph; an artificial moon was masking the solar disk (courtesy: Paris Observatory).

Figure 32: Instability of the solar prominence of 18 June 1925 in the CaII K line from 09:11 to 11:03 UT. The image at left is a ‘section’ spectroheliogram, obtained by moving the entrance slit by steps of 22” The five line profiles of CaII K (2.15 Å wide) at the bottom are those of the cross section AB (courtesy: Paris Observatory).

SDO/NASA since 2010 (45 s cadence for each waveband), but it is also the case with the EIT telescope onboard SOHO/ESA/NASA since 1996 (with a lower cadence and spatial resolution than SDO).

Figure 33 displays one of the ‘treasures’ of the 10 solar cycles Meudon collection, this is the eruption of a huge solar prominence observed just after WW1 in May 1919 (after a total interruption during the war). Observations were performed in the Call K3 line with an artificial moon superimposed upon the solar disk to allow long exposure time, as prominence material is faint.

The July 1946 group of Figure 28 produced the strong solar flare of Figure 34, and a huge geomagnetic storm. This phenomenon is one of the most energetic eruptions ever observed. André Danjon, the Director of Paris-Meudon Observatories, was there during this event (he often spent the summer in Meudon) and was fond of solar observations (as well as mushrooms from the forest). However, Gualtiero Olivieri, who was the observer, reported that “...his advices and commands given to the observers did not help them to stay quiet and keep cool.” Flares originate in active regions and have a magnetic origin. The magnetic energy is stored in sunspot groups, such as the big ones of Figure 28; it is proportional to the surface and to the square of the magnetic field intensity. Unstable configurations often occur near the solar maximum and just after, and trigger huge flares, which convert magnetic to kinetic energy, radiation and heat. The 1946 event illustrates the importance of historical data. It allowed Aulanier et al. (2013) to predict the maximum possible energy of a solar flare, about $5 \times 10^{26}$ Joule; this is 10 times the one ever measured by satellites of the modern era and could also be 10 times the value of the famous Carrington event of September 1859 as estimated by Hayakawa et al (2023). The average energy of solar eruptions
Figure 33: Instability of a solar prominence seen in Ca II K3 on 27, 28 and 29 May 1919, observed with Meudon spectroheliograph. The times are indicated in the picture (courtesy: Paris Observatory).

Figure 34: The major two-ribbon solar flare of 25 July 1946 observed in Hα with Meudon spectroheliograph (the times are, from the right to the left, 15:37, 16:14, 16:24, 17:57, 18:15 UT). The leftmost image at 16:58 UT was got in the He I D3 5876 Å line. The short-duration flash phase (lasting minutes) occurred at 16:14 UT. Two bright ribbons (17:57, 18:15 UT) formed during the long-duration gradual phase (lasting hours) and corresponded to the impact of energetic particles on the chromosphere (courtesy: Paris Observatory).

lies around $10^{25}$ Joule.

6 THE INTERNATIONAL CONTRIBUTION OF MR AND MRS D’AZAMBUJA

Mr and Mrs d’Azambuja can be considered pioneers in the coordination of international campaigns of solar observations and scientific collaborations. They first offered the possibility for each observatory to receive (upon request) a photographic copy of Meudon daily images.
They soon initiated the publication of synoptic maps and flare catalogues, and later the worldwide dissemination of messages and alerts within the framework of an international solar activity survey.

International cooperation in solar observing began early. Hale (1931) organized a network of 23 visual spectrohelioscopes, which were installed in many stations to establish a patrol of chromospheric activity. In 1932, the Solar Commission of the IAU split into four groups and Mr d’Azambuja became Chairman of the Subdivision dedicated to chromospheric events. He was in charge of coordinating stations located in America, Europe, Asia, Australia and New Zealand (d’Azambuja, 1939). Flare observations were collected and compiled by Meudon, which published lists, indices and tables in the Bulletin for Character Figures of Solar Phenomena, edited in Zürich from 1928. It was renamed the Quarterly Bulletin on Solar Activity in 1939 and was transferred in 1976 to Mitaka, Japan (https://solarwww.mtk.nao.ac.jp/en/wdc/qbsa.html). The Quarterly Bulletin ... was delivered to 60 countries until 2009.

Mr d’Azambuja took advantage of the multi-layer (photosphere and chromosphere) images produced by Meudon. In 1913 he started the drawing of synoptic charts of structures of the upper layer (filaments and plages from CaII K and Hα spectroheliograms) and the lower layer (sunspots from CaII K1v images). A preliminary map was published after WWI (d’Azambuja, 1921). At the 1925 symposium of the IAU, 30 rotations were shown, and the diffusion of the maps was proposed. The work involved reporting, for each synodic rotation of the Sun, the average position of solar structures on rectangular maps, with the longitude on the abscissa and the latitude on the ordinate (Figure 35). Each rotation was identified by a Carrington number (starting on 9 November 1853). The collection began with rotation 876 (March 1919) and ended with rotation 2008 (October 2003). Each map was accompanied by various tables characterizing the observed features. The synoptic charts were first published in the Annales of the Paris-Meudon Observatory, then in l’Astronomie.

Mrs d’Azambuja took a major part to this long-term undertaking, and the synoptic maps were the basis of the couple’s 1948 research memoir about solar filaments. She was also strongly involved in the Quarterly Bulletin ... flare catalogues and in the preparation of the French program of the International Geophysical Year in 1957, together with Raymond Michard. He initiated new instruments dedicated to the survey of solar activity, such as the flare spectrograph (at Pic du Midi) or high-cadence Lyot heliographs (at Meudon and Haute Provence). The first magnetograms of active regions were produced with the powerful 7-meter research spectrograph of the d’Azambujas (Michard and Rayrole, 1965). After Mrs d’Azambuja retired in 1959 a forecasting centre of solar activity was open in Meudon, and this operated until 1997. The synoptic map program was continued by other people, but stopped in 2003 when the last person drafting the maps retired. Existing maps can be downloaded at https://bass2000.obspm.fr/lastsynmap.php.

In order to investigate the terrestrial impact of solar flares, such as ionospheric perturbations and events carried by the solar wind (occurring generally within a 24-hour delay), from 1928 messages (called ursigrams) were sent to the geophysical community by several countries under the auspices of the ‘Union Radio Scientifique Internationale’ (URSI). An index (0–5) provided the solar activity level. The messages were interrupted by WWII, but the IAU recommended the Commission chaired by L. d’Azambuja examine the question of ‘... the prediction of terrestrial phenomena of solar origin and the determination of active areas’ (d’Azambuja, 1949). Ursigrams restarted in 1947 using information provided by many observatories and sent to Meudon by telegram. It was not possible to predict solar flares, but the messages indicated the location of active regions and the occurrence of flares. As this tool was very useful, it was soon extended. The International Ursigram and World Days Service (IUWDS) was created in 1962 and favoured the development of forecasting methods. This was replaced in 1996 by the International Space Environment Service, with 15 Regional Warning Centres (RWC) at various latitudes. Meudon was one of these, and the Space Weather Prediction Centre in Boulder (USA) today is probably the most important facility. The Scientific Committee on Solar Terrestrial Physics (SCOSTEP) also coordinates international research programs to improve our understanding of solar instabilities and their precursor events. This implies campaigns of multi-wavelength observations, such as the Max Millennium program.

7 CONCLUDING REMARKS

Meudon spectroheliographs produce monochromatic images of the chromosphere in CaII K3 and Hα, and of the photosphere in the blue wing (K1v) of the CaII K line, on a daily basis since 1908. The collection extends now over 10.5 solar cycles and contains more than 100000 spectroheliograms freely available at https://bass2000.obspm.fr. However, between
1919 and 1954, a lot of special and unique observations were produced by Mr and Mrs d’Azambuja with the large 7-metres spectroheliograph dedicated to research. They studied together many unusual spectral lines, such as photospheric lines of FeI, CaI, HeI or SrII, and chromospheric lines of infrared CaII or HeI. Some of their observations, such as HeI 10830 Å, were the first world-wide, and they demonstrated that the initial choice of CaII K3, K1v and Hα was the best for imaging spectroscopy of the photosphere and the chromosphere. The d’Azambujas intensively studied the morphology of solar filaments, which was described in their pioneering 1948 memoir. Besides, many dynamic and rare events were recorded by them with the spectroheliographs dedicated to systematic observations, such as huge flares or prominence ejections. Of course, the spectroheliographs were not designed for high cadence phenomena, as their goal was low cadence and long-term observations of the solar cycles. For that reason, instruments using Lyot Hα filters were used at Meudon for 50 years (1954–2004).
to record fast-evolving events. The final sentence in the d’Azambuja’s memoir was premonitory:

… the cinematic registering of events assumes international cooperation, in such a way that a continuous movie definitely could be made for a time span reaching half a rotation. (d’Azambuja and d’Azambuja, 1948: 206).

It so happens that the GONG Hα network, the LASCO/SOHO coronagraphs and the AIA/SDO EUV instruments all fully meet this wish.

Today, observations with the modern spectroheliograph continue and the 115-year old collection of Meudon is intensively used for long term studies, i.e. reconstructions of solar parameters such as plage areas or irradiance (Chatzistergos et al., 2020; 2021). In order to improve the number of annual observations, a collaboration between researchers and amateur astronomers was set up in January 2023, based on the Solar Explorer (SOLEX) mini spectroheliograph (Buil et al., 2023; Malherbe et al., 2023) which provides narrow-band monochromatic Hα images. Meanwhile, in January 2024 a new high cadence Hα instrument at Côte d’Azur Observatory (MeteoSpace, Calern Plateau) replaced the old Meudon instruments that used Lyot filters (Malherbe et al., 2022 e.g., see https://solar.ftp.oca.eu/pub/DEPOT/MTS_CAL ENDAR.html).

8 NOTES

1. The Solar Atmosphere. It is composed of three layers: (1) the photosphere (the visible surface, temperature decreasing from 6000 K to 4500 K in 300 km) with dark magnetized sunspots and bright faculae around; (2) the chromosphere above (temperature increasing from 4500 K to 8000 K in 2000 km) with dark filaments and bright plages (corresponding to faculae in the photosphere); and (3) the ionized and hot corona (2 million K). The corona extends to a million kilometres and gives rise to the solar wind (charged particles), which propagates into the interplanetary medium. The chromosphere and the corona require spectroscopic means to reveal their structures, respectively via absorption lines of the visible spectrum or emission lines of the ultraviolet spectrum. The solar atmosphere follows a 11-year activity cycle and a 22-year magnetic cycle. Flares and coronal mass ejections occur in active regions a few years around the solar maximum; the next maximum of the current cycle (number 25) is forecasted for 2025. The symbol K above (Kelvin) is the unit of the absolute temperature, related to the Celsius temperature by $T(K) = T(°C) + 273.15$.

2. The Wavelength. Electromagnetic waves, such as the visible light, are detected by telescopes. They form a continuous spectrum (such as the rainbow) with superimposed spectral lines, revealing the presence of atoms, ions or molecules. In the visible or ultraviolet spectrum, the lines are identified by their wavelength, measured in nanometres (1 nm = $10^{-9}$ m), but spectroscopists often prefer the Angström (1 Å = 0.1 nm = $10^{-10}$ m). The visible solar spectrum (4000 Å–7000 Å) reveals thousands of absorption lines, while emission lines occur in the ultraviolet spectrum (below 4000 Å) or at the limb.

3. Solar Structures. Dark sunspots are regions of intense magnetic fields (0.1–0.3 T). Bright faculae or plages form, together with sunspots, active regions, and exhibit smaller magnetic fields (0.0–0.05 T). Dark filaments, also called prominences when seen at the limb, are thin and high structures (50000 km) of dense material suspended in the corona by weak magnetic fields (0.001 T). The symbol T is the unit of magnetic field (Tesla); the Gauss (1 G = $10^{-4}$ T) is also used. Flares occur in zones of unstable fields; reconnections convert magnetic energy into kinetic energy (ejections), radiation (X-rays) and heat (brightenings).

4. The Doppler Effect. When a light source moves in the observer’s direction, the spectral lines are shifted towards shorter wavelengths (blue-shifted). Conversely, if the source moves in the opposite direction, lines are shifted towards longer wavelengths (red-shifted). The Doppler shift $w(Å)$ is a wavelength shift, proportional to the projection $V$ (km/s) of the velocity vector along the line-of-sight (it is also called the radial velocity, positive towards the observer in solar physics): $w = -λ (V / C)$, where $λ$ is the line wavelength (Å) and $C$ is the velocity of light ($3 \times 10^5$ km/s).

9 ACKNOWLEDGEMENTS

The author thanks Dr. Jean-Claude Vial for reading the manuscript and the anonymous referees for helpful comments and suggestions. He is indebted to I. Bualé and F. Cornu for providing spectroheliograms of the Meudon solar collection, and for exploring the photographic archives of the instruments and characters.

10 MPEG4 MOVIES

Movie 1: the Meudon spectroheliograph in 1942 (courtesy Paris Observatory), on-line at:
11 REFERENCES


---


He first worked on solar filaments and prominences using multi-wavelength observations. He used the spectrographs at the Meudon Solar Tower, the Pic du Midi Turret Dome, the German Vacuum Tower Telescope, THEMIS (Tenerife) and developed polarimeters.

He proposed models and MHD 2D numerical simulations for prominence formation, including radiative cooling and magnetic reconnection. More recently, he worked on the quiet Sun, using satellites such as HINODE (JAXA), IRIS (NASA), and MHD 3D simulation results.

He was responsible of the Meudon spectroheliograph from 1996 to 2023.